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Using airborne laser scanning to monitor tree migration in the boreal–alpine transition zone

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Abstract

The boreal tree line is expected to advance upwards into the mountains and northwards into the tundra due to global warming. The major objective of this study was to find out if it is possible to use high-resolution airborne laser scanner data to detect very small trees — the pioneers that are pushing the tree line up into the mountains and out onto the tundra. The study was conducted in a sub-alpine/alpine environment in southeast Norway. A total of 342 small trees of Norway spruce, Scots pine, and downy birch with tree heights ranging from 0.11 to 5.20 m were precisely georeferenced and measured in field. Laser data were collected with a pulse density of 7.7 m^{-2}. Three different terrain models were used to process the airborne laser point cloud in order to assess the effects of different pre-processing parameters on small tree detection. Greater than 91% of all trees >1 m tall registered positive laser height values regardless of terrain model. For smaller trees (<1 m), positive height values were found in 5–73% of the cases, depending on the terrain model considered. For this group of trees, the highest rate of trees with positive height values was found for spruce. The more smoothed the terrain model was, the larger the portion of the trees that had positive laser height values. The accuracy of tree height derived from the laser data indicated a systematic underestimation of true tree height by 0.40 to 1.01 m. The standard deviation for the differences between laser-derived and field-measured tree heights was 0.11–0.73 m. Commission errors, i.e., the detection of terrain objects — rocks, hummocks — as trees, increased significantly as terrain smoothing increased. Thus, if no classification of objects into classes like small trees and terrain objects is possible, many non-tree objects with a positive height value cannot be separated from those actually being trees. In a monitoring context, i.e., repeated measurements over time, we argue that most other objects like terrain structures, rocks, and hummocks will remain stable over time while the trees will change as they grow and new trees are established. Thus, this study indicates that, given a high laser pulse density and a certain density of newly established trees, it would be possible to detect a sufficient portion of newly established trees over a 10 years period to claim that tree migration is taking place.
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Keywords: Forest monitoring; Global change; Laser scanning; PCQ sampling; Small trees; Tree growth; Tree line; Tree migration

1. Introduction

Elderly people living in the high north and close to the mountains claim that the arctic and alpine tree lines, respectively, have moved northwards into the tundra and upwards into the mountains during their lifetime. Such testimonies from aborigines and local people in northern Europe as well as in North America can hardly be considered as scientific evidence, but when considered in the context of concurrent scientific observations of global warming, they indicate that rapid changes are likely taking place in these marginal areas as far as tree growth is concerned (ACIA, 2004). The tundra and the mountains are not separated from the boreal forest by a distinct dividing line, but by a transition zone characterized by gradients in background factors like climate, snow dynamics, and land use. Since such factors typically are influenced by local conditions like topography (Callaghan et al., 2002), it is evident that any effects of global warming will have a local expression in terms of tree migration and the increased growth of established trees.

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A need exists to monitor vegetation changes caused by natural and human-induced processes in these transitions zones (Callaghan et al., 2002). For vast areas like the boreal–tundra transitions zone with a circumpolar extension, remote sensing is likely to be the most efficient means for monitoring, either by providing repeated wall-to-wall coverage or based on sampling, preferably at fixed locations, over time. Some attempts have been made to detect changes in vegetation and tree cover in the tundra–taiga transition zone using various kinds of remote sensing techniques. Typically such studies have relied on some kind of optical remote sensing utilizing coarse resolution data from instruments like NOAA AVHRR, Terra/Aqua MODIS, SPOT VEGETATION, and Landsat TM. A good overview of previous studies of this kind is provided by Heiskanen (2006). However, it is obvious from the spatial resolution of these optical sensors that they are not able to capture local changes over short time periods. Given that small trees growing under such marginal conditions have a height growth of, say, 0–5 cm per year, many years of growth is required to give a significant signature response of a coarse-resolution optical remote sensing dataset.

Laser remote sensing from airborne or satellite platforms represents a promising technology for precise estimation of biophysical parameters of trees and forests at different scales like individual trees (e.g. Hyyppä et al., 2001; Persson et al., 2002; Solberg et al., 2006), groups of trees (e.g. Lim et al., 2003; Næsset, 2002, 2004a), forest stands (e.g. Holmgren, 2004; Means et al., 2000; Næsset, 1997, 2002, 2004a,b), states and nations (Nelson et al., 2003b, 2004), and continents (Harding and Carabajal, 2005; Lefsky et al., 2005). As far as effects of climate change on trees along the arctic and alpine tree lines are concerned, two processes need to be monitored, namely the change in growth of already established trees and expansion of the forest by establishment of new trees further north and into the mountains where trees previously were not present. These effects are important not only because they represent significant changes of the vegetation communities in the transitions zones, but also because they may have a significant impact on total carbon sequestration in these ecosystems. It has been shown recently that tree height growth, at least on trees of a certain size, can be estimated on an individual tree basis with an RMSE of 0.43 m using high-density airborne laser scanner data ($\sim$10 pulses per m^2) over a relatively short time period (five years) (Yu et al., 2006). Even with airborne laser data of lower density ($\sim$1 pulse per m^2) it has been shown that a significant growth can be detected for geographical areas like forest stands with a size of, say, 1–2 ha, over such a short time period as two years, although with an RMSE of no better than 0.53 m (Næsset & Gobakken, 2005). However, longer time intervals with more pronounced growth will allow more precise estimates of growth. On the other hand, in areas with lower growth-rates like in the alpine transition zone it takes a longer observation period to detect growth as a significant change in the statistical sense.

Even though detection of individual trees has been one of the major directions of research in the efforts to derive forestry-related information from airborne laser scanner data, most studies have focused on larger, mature trees. Næsset and Bjerknes (2001) estimated tree heights and stem numbers in young forest based on medium-density laser scanner data ($\sim$1.2 pulse per m^2), but they did not detect individual trees. However, they were able to explain 83 and 42% of the variability in mean tree height and stem number, respectively, on small field plots using regression analysis and canopy metrics derived from the laser data as explanatory variables. The mean tree height of the plots ranged between 1.8 m and 6.0 m.

The smaller a tree is, the less likely is it that it can be detected by airborne laser scanning. The smaller a tree is, the less likely is it that it will be hit by a laser pulse and the more likely is it that a laser pulse actually hitting and being reflected from the tree will be classified as a ground return rather than an echo from an object above the ground surface. The closer the objects of interest are to the ground surface, the more uncertain the classification of those objects. The classification error will be affected by the way the digital terrain model is established. A number of different algorithms are used to derive terrain data from laser point clouds, and they all have parameters that control the degree of smoothing. Thus, it is a complicated issue to reconstruct the “true” fine-scale morphology of the terrain. However, this reconstruction is essential for the outcome of classification of laser echoes as reflections from the ground-surface itself and small terrain objects with positive height values close to the surface. It is quite common to find a number of terrain objects other than trees close to the ground surface, e.g., tussocks, hummocks, rocks, boulders. These objects, depending on their size and shape, may be classified as terrain or as distinct objects rising above terrain. Without additional information, it may be difficult to distinguish between a large rock and a small tree. Thus, in a scanning laser-based inventory of small trees, misclassifications will occur, mixing trees, terrain objects, and terrain. These misclassifications will have a significant impact of the reliability of tree numbers. In a monitoring context, however, i.e., multi-temporal measurement of small trees over time, misclassification is not necessarily a problem since the terrain and terrain objects will remain stable while the trees will change in terms of occurrence and size.

In this study, we wanted to find out if it is possible to use high-resolution airborne laser scanner data to detect very small trees — the pioneers that are pushing the tree line up into the mountains and out onto the tundra. We worked in a sub-alpine/alpine environment, which we considered to be a relevant case representing the large transitions zones of the northern hemisphere that we believe will be sensitive biomes for monitoring effects of global change over the coming decades. The specific objectives were 1) to assess the success of detection of individual small trees in the alpine tree line, and to evaluate how 1a) tree species, 1b) tree size, and 1c) different terrain models influenced the detection success. Furthermore, we 2) assessed the accuracy of tree height estimation based on the laser measurements. Finally, 3) the success of detection of terrain objects (e.g., hummocks, rocks) was analyzed, and 4) an error assessment was conducted to evaluate how different terrain models influenced on tree detection omission and commission errors.